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Volume-controlled grouting for compensation of drainage-induced settlements

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SYNOPSIS: The excavation of an underground metro frequently involves materials of poor geotechnical characteristics. Under certain conditions, improvement of the strength and stiffness of the ground is recommended to facilitate the excavation. Drainage of silty/clayey layers is generally reckoned as an efficient action before excavation. Boreholes for drainage can be drilled and activated for a required time. Dissipation of pore pressures may lead to a sufficient increase of short-term resistance, which is going to be mobilized during excavation. However, drainage may induce surface settlements, which can affect the buildings in the area of the construction works. In order to compensate these settlements grout injections can be carried out to produce an artificial volumetric increase. Sometimes the propagation may result uncontrolled as a consequence of the heterogeneity of the soil mass. Therefore, especially when historical buildings are involved, volume-controlled grouting may necessitate avoiding damage. As innovative solution, grout can be injected along a rod inflating pockets of special tissue and a prescribed volumetric expansion can be given. In this note the results of a numerical analysis are illustrated to demonstrate the efficiency of volume-controlled grouting with reference to an hypothetical case where enlargement of an existing tunnel section is planned.

1. INTRODUCTION

The excavation of an underground metro frequently concerns materials of poor geotechnical quality. Under certain conditions, an improvement of the strength and stiffness of the ground is recommended to facilitate the excavation. Several measures can be undertaken to this aim, for example, drainage of silty/clayey layers is generally reckoned as an efficient action before the excavation (see references [1,2]).

Drainage produces an increase in effective stress and consequently the available short-term strength around the excavation. However, as a secondary effect, it may lead to important surface settlements, which in turn can compromise the stability of nearby buildings. It is therefore necessary to apply specific countermeasures that can minimize or compensate these settlements.

Injections of grout to artificially increase the soil volume (compensation grouting) are frequently used to limit ground settlements in large tunneling projects (e.g. Mair et al.[3]). The traditional compensation grouting consists of installing in the area to protect a system of tube *a manchettes* located in predefined positions. A first injection phase is usually performed to stabilize the soil, then a second injection phase is realized if surface settlements occur during the excavation (concurring compensation). A monitoring system gives all the necessary information to manage properly the operations. The success of the application depends on many factors in relation to the physical characteristics of both the grout and soil (Au et al. [4]).

If the ground is heterogeneous, even if a monitoring system is set up, the control of grout pathways and distribution of volumetric expansion may result difficult and the efficiency of the countermeasure be compromised.

In this case, one solution may be to pump the grout into small inflatable pockets of a special tissue aligned in a hollow rod with holes. The benefits of the solution are evident: the volumetric expansion is fully predictable and the intervention may be differentiated to better counteract the evolution of the surface settlements.

A FLAC numerical model has been set up to simulate with reference to a hypothetical case the displacement field as combination of drainage and volume-controlled grouting. The results of the simulation are reported and the efficiency of the proposed technique is highlighted.

2. CONCEPTUAL SCHEME OF THE INTERVENTION AND NUMERICAL MODEL

In Figure 1 an application of combined drainage and volume-controlled grouting is shown where an enlargement of a tunnel section, previously excavated by TBM, is planned. If the quality of the soil is very poor, before the enlargement radial drains may be activated. The time occurring for the consolidation depends on the soil geotechnical parameters, especially on the coefficient of consolidation. Whilst the consolidation by drainage takes place the inflatable pockets may help with a double effect: (1) volume compensation is provided, (2) acceleration of the consolidation is achieved.

The FLAC model refers to a hypothetical situation where a 30m-deep gallery with a diameter of 10m is excavated in low permeability material of poor geotechnical properties (Figure 2). A plane strain/plane flow condition is considered. A crown of equally-spaced radial drains is located 4.5m far from the center (detail of the mesh in Figure 3). Two horizontal boreholes departing from the sidewalls with inflatable pockets are included for simulating the grouting. The spacing along the direction normal to the plane is assumed small enough for the plane conditions to hold.

The simulation steps are as follows: (1) excavation of the inner section, 2) activation of drains and inflatable pockets.

To emphasize the efficiency of combined drainage and grouting, the solution is compared to a solution with drains only. As far as the boundary conditions are concerned, with respect to the fluid flow the water table is at the upper boundary, the bottom boundary and the axis of symmetry are no-flow boundaries and the pressures at the vertical right boundary are set as hydrostatic.

The boundary conditions for the displacements and tractions are the following: free displacement at the top boundary (zero traction), nil displacements at the right and bottom boundary, nil horizontal displacement and nil vertical traction at the axis of symmetry.

The following mechanical parameters have been used as typical for a clayey silt: bulk unit weight γ=23KN/m^3, drained elasticity modulus *E*=5MPa, drained Poisson coefficient ν=0.25. With respect to hydraulic conductivity *K*, the sensitivity of the solution to the parameter has been investigated by imposing the following three values: 1.E-07m/s, 1.E-08m/s, 1.E-09m/s.

The expansion of the pockets is simulated by applying an increasing pressure at the inner boundaries until maximum expansion (40cm) is reached. Then, the material inside is substituted by a material whose mechanical properties are those of a solid concrete mixture (see Figure 3). The FLAC option *Set Large* is utilized. Therefore, the mesh is adjusted at each time-step.

3. RESULTS

3.1 *Case with drainage only*

With reference to the case of drainage only, it is seen that the increase of effective stress around the drains is conspicuous and leads fast to attain the required values of short-term strength for the enlargement in safe conditions (see Figure 4 for *K*=1.E-08m/s).

In Figure 5 the evolution at point A (see Figure 3) of the isotropic effective stress σ_0' with time and for each pre-selected *K* value is given. As expected the larger is the hydraulic conductivity the faster is the increase of σ_0'. It can be stated that the efficiency of the drainage is guaranteed for materials with medium-low hydraulic conductivity. The increase of the short-term strength is pronounced and acquired rather soon.

However, the fast increase of σ_0' may lead to the development of unsustainable surface settlements. Therefore, the higher is *K*, the more the compensation is required, as shown in the Figures 6 and 7. In Figure 6 the evolution of the surface settlements with time for k=1.E-08m/s is given: the maximum values are: 2.5cm after 12 hours, 5.3 cm after 1 day, 13.4cm after 5 days. In Figure 7 the maximum settlement after 1 day is plotted against the number of drains in half a section for each selected *K* value. Beyond a threshold of 10 drains the response of the system stabilizes and efficiency is reduced.

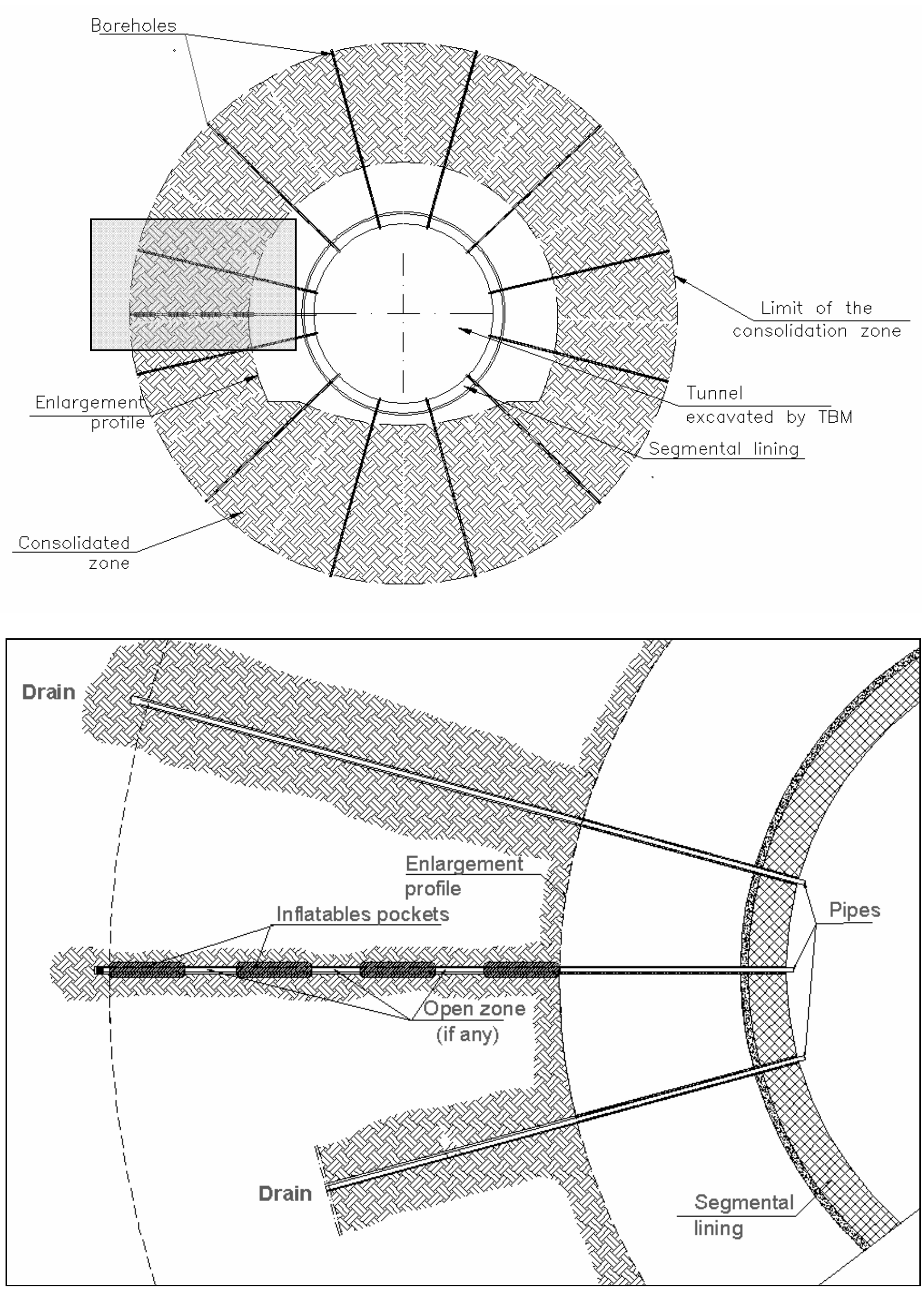

Figure 1. Combination of radial drainage and volume-controlled grouting

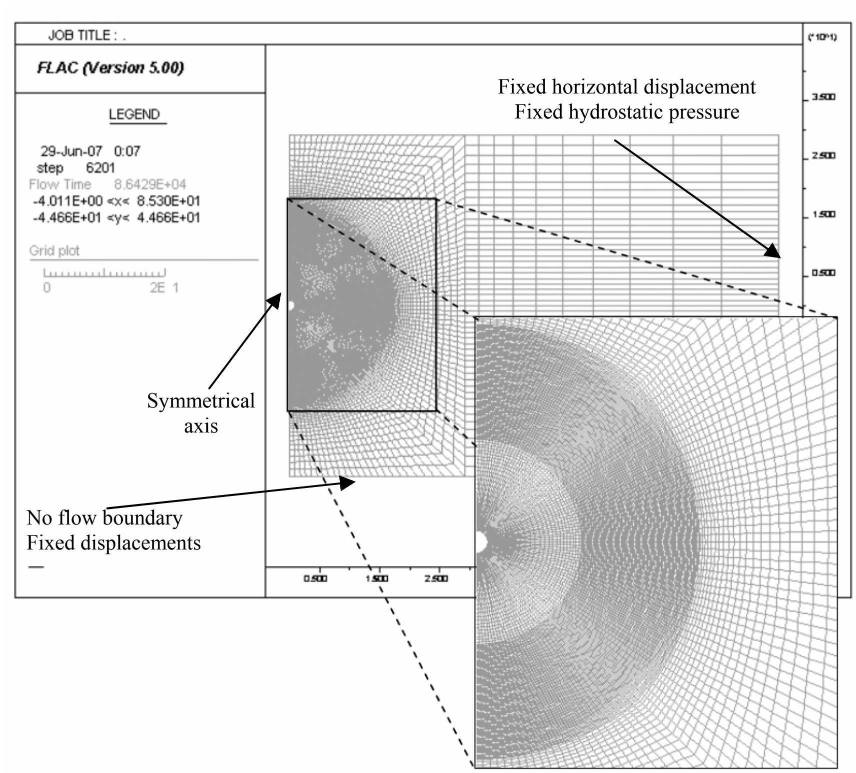

Figure 2. FLAC model grid

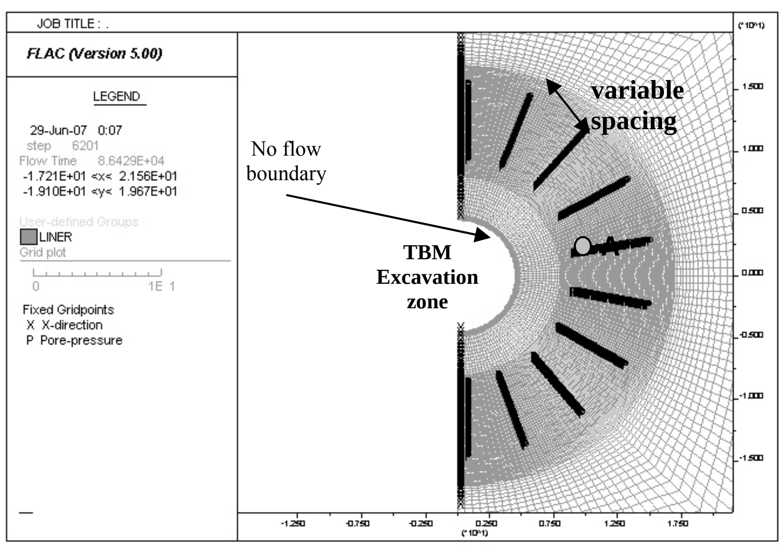

Figure 3. Scheme of the simulation - detail of the FLAC mesh close to the pre-excavated tunnel (case drains only)

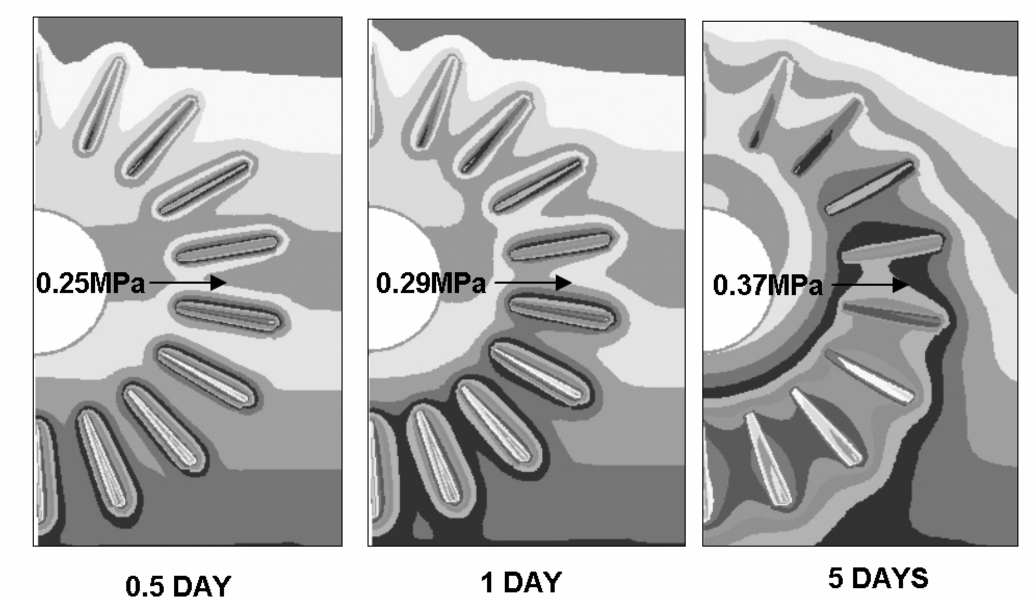

Figure 4. Pattern of the isotropic effective stress σ_0' close to the crown of 10 drains for K=1.E-08m/s

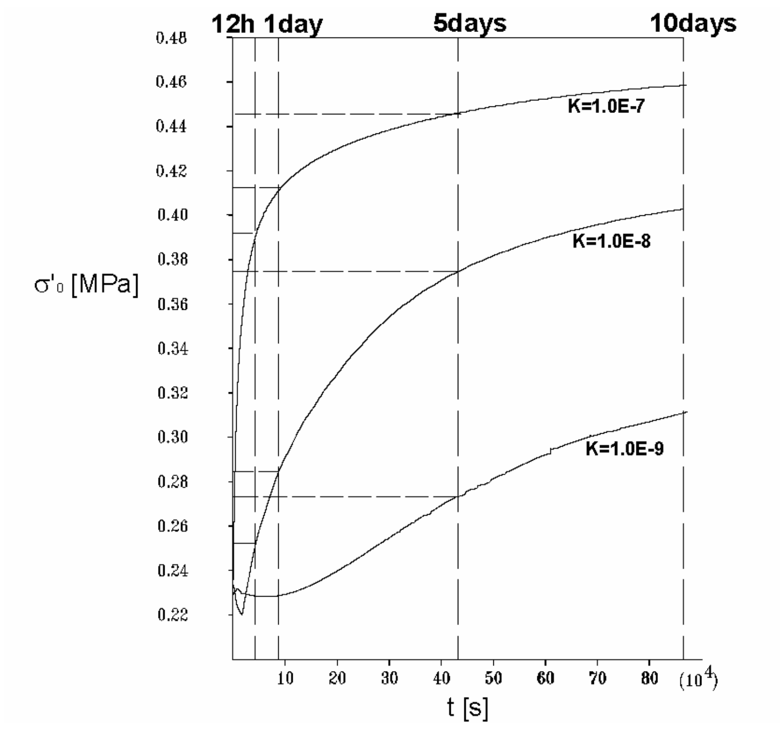

Figure 5. Evolution of σ_0' with time at node A for each selected K value (case 10 drains)

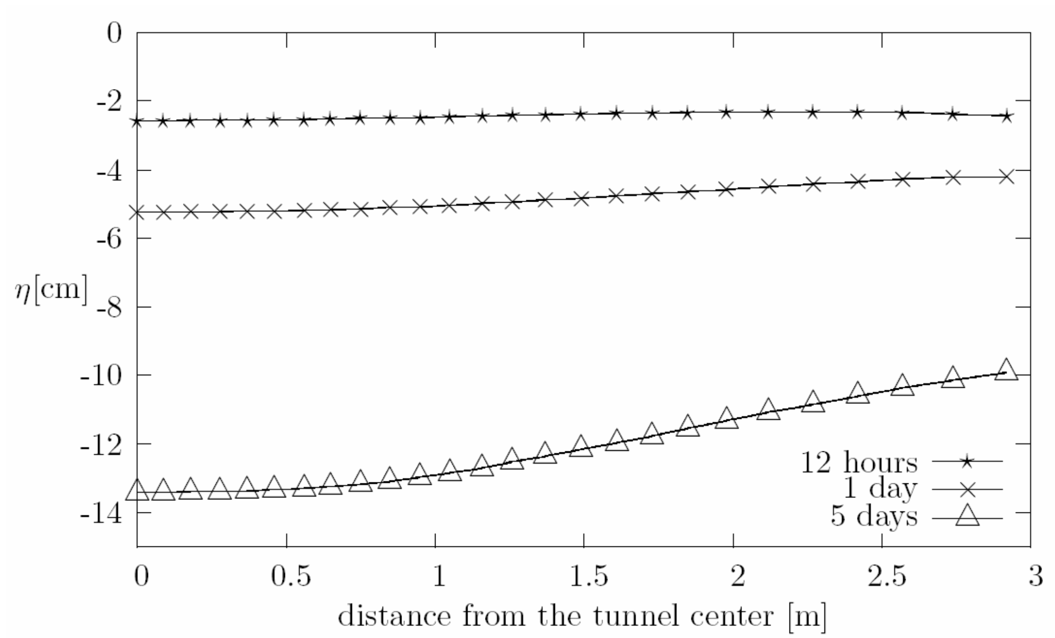

Figure 6. Surface settlement with time (case of 10 drains and K=1.E-08m/s)

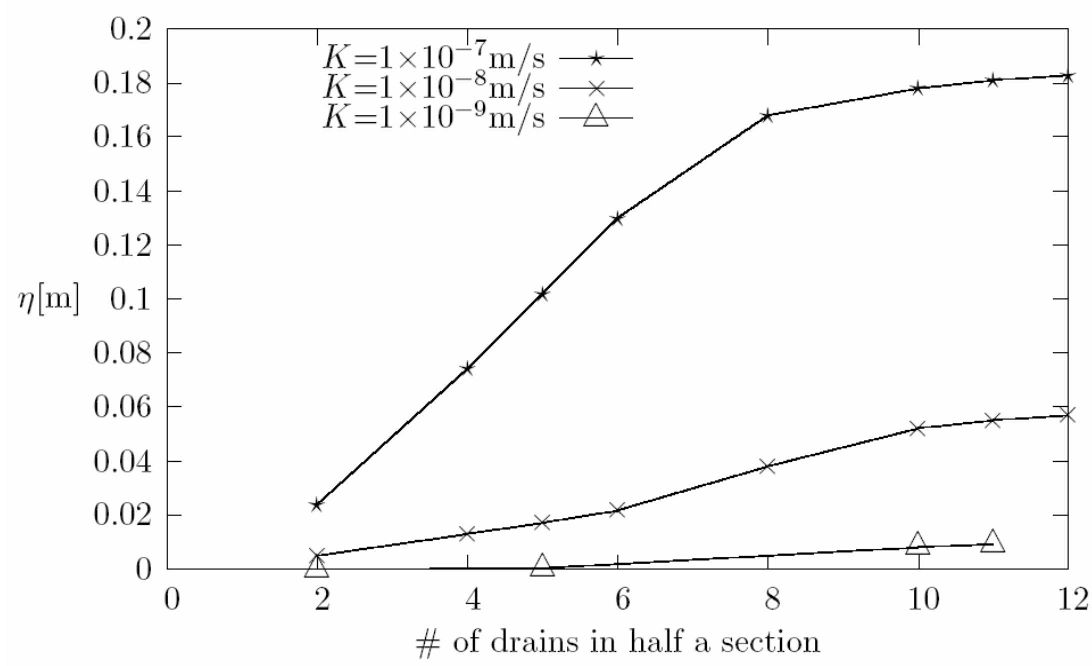

Figure 7. Maximum surface settlement at 1 day plotted against the number of drains and per each selected K value

3.2 *Case with inflatable pockets*

In Figures 8a and 8b the detail of the expansion is shown. The inflation of the pockets is simulated by applying an internal pressure to zero-thickness interfaces (see Wisser et al. [5]). In Figure 8a the pressure is applied. In Figure 8b once the maximum expansion is reached, the void is filled with a rigid material. The FLAC mesh is adjusted with the expansion to avoid line superposition.

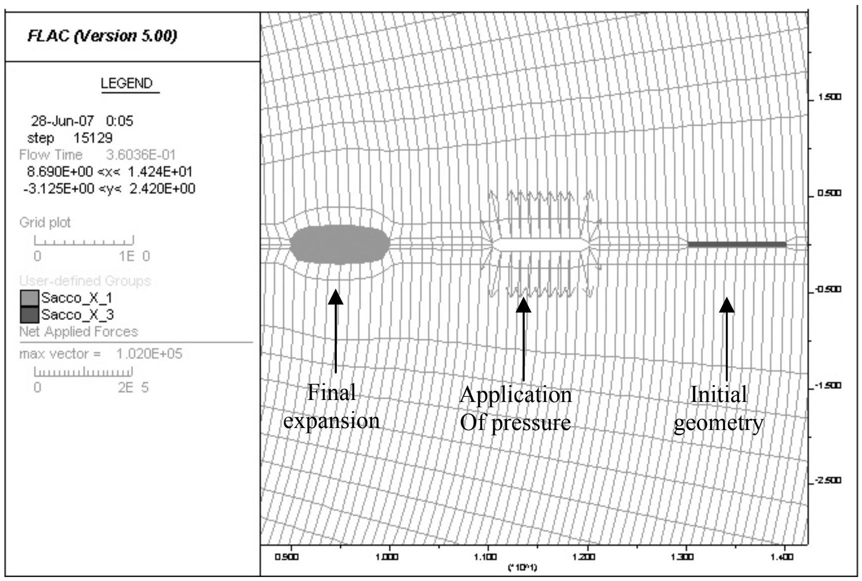

Figure 8a. Expansion of the inflatable pockets (application of pressure)

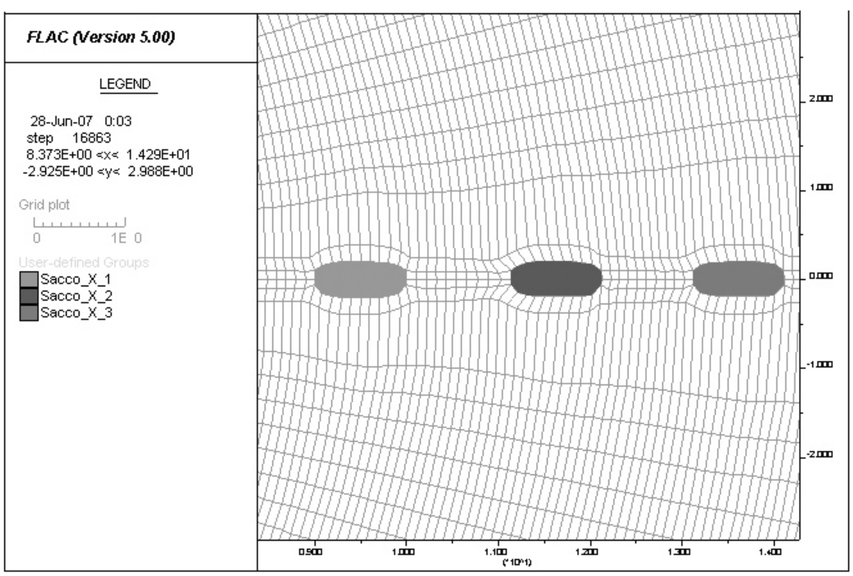

Figure 8b. Expansion of the inflatable pockets (final configuration)

In Figure 9 the pattern of σ_0' for active volume-controlled grouting is displayed.

The comparison with the Figure 4 (case of drainage only) highlight the effect of the inflated pockets on the evolution of the σ_0'.

At the same manner, in Figure 10 the comparison in terms of surface settlements is displayed for the three selected values of *K*. As expected the effect of the inflatable pockets is superimposed on the effect of drainage. The amount of the compensated settlement is rather irrespective of the permeability value and then it is relatively more significant for low permeability. To the contrary the benefit of the technique reduces with the increase of permeability. The reduction of maximum settlement in this specific situation and for only two equipped boreholes is around 7mm (20% for K=1.E-08m/s).

However one must account for the three-dimensionality of the problem to derive a precise relation among number of boreholes per meter measured normal to the section, spacing of the pockets, maximum allowed inflating of the pockets versus the reduction of settlements.

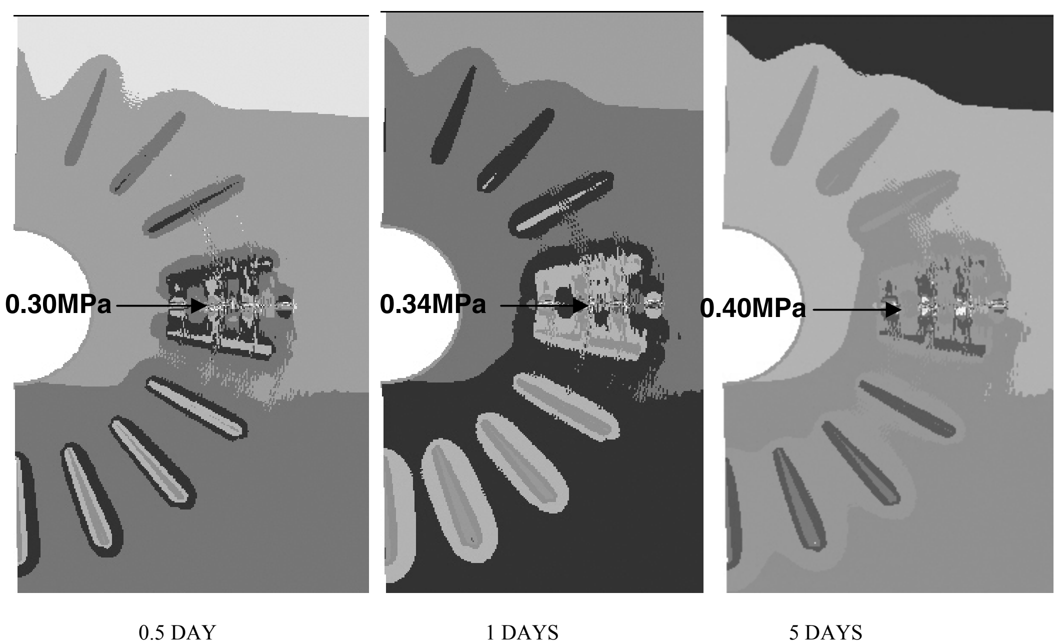

Figure 9. Pattern of the isotropic effective stress σ_0' close to the crown of drains for K=1.E-08m/s, 10 drains and volume-controlled grouting

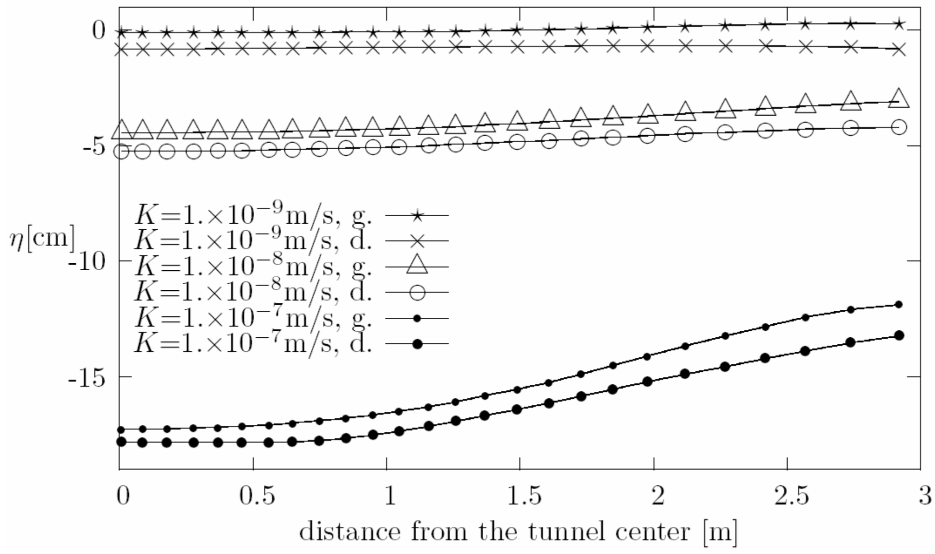

Figure 10. Surface settlements for each selected K; comparison between drains-only (d.) and drains+grouting (g.) cases (10 drains) after 1 day

4. CONCLUSIONS

Superficial excavations for metro lines with low overburden frequently involve highly deformable argillaceous materials. Under these conditions enlargements of pilot tunnel excavated by TBM may result complicated.

Various techniques may be used to improve the quality of the soil and usually, drainage through radial boreholes departing from the lining is considered as an appropriate solution.

The time required for consolidation depends on the mechanical properties of the soil, however for superficial deposits it is generally limited to few days. As a consequence of the drainage, the soil volume is reduced and settlements arise that may compromise the stability of the buildings in the area affected by the underground works. A compensation of the deformation is suggested. In this note the results of a simulation of the effect of so-called volume-controlled grouting is reported. Pockets aligned along a rod are inflated by a grout producing a local volumetric increase. The simulation refers to a couple of rods equipped with these inflatable pockets. The compensation achieved is 20% for K=1.0E-08m/s. The result is promising, also in terms of increase of short-term strength, therefore the technique will be further engineered and applied. One possible development is to dispose along the same rod the apertures for the drainage and the inflatable pockets.

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